



Variations in the westerlies in Central Asia since 16 ka recorded by a loess section from the Tien Shan Mountains

Jia Jia*, Hao Liu, Fuyuan Gao, Dunsheng Xia

MOE Key Laboratory of West China's Environmental System, College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China



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ABSTRACT

Central Asia comprises a vast area of arid terrain which has an important impact on the global climate system. Although still debated, the pattern of climatic variations in central Asia is regionally distinctive and does not appear to be strongly related to changes in insolation. To understand the climatic evolution of central Asia, as well as its forcing mechanisms, it is necessary to characterize variations in the Westerlies, which have had a major influence on climate change in the region. Past variations in the Westerlies are commonly reconstructed from records of the composition, grain-size and mass accumulation rate (MAR) of loess and the eolian component of lacustrine sediments which are commonly mixed by the signal of surface atmospheric circulation. Here we present the results of grain-size analysis of a section of last glacial and Holocene loess deposits in the Tien Shan Mountains. The results indicate that the strength of the Westerlies was weakest during the last deglacial and early Holocene (16–6 ka), strongest during the mid-Holocene (6–3.1 ka), and moderate during the late Holocene (3.1–0 ka). By comparison with an independent record of humidity, we propose that the Westerlies were an important driver of moisture variations in central Asia, with strong Westerlies circulation resulting in high precipitation and vice versa during the past 16 kyr.

1. Introduction

Central Asia experiences an arid climate and is dominated by desert. It plays an important role in the global climate system via the emission of huge quantities of eolian dust, which have a large impact on the chemical properties of the atmosphere at mid-latitudes and over the Pacific Ocean (Maher, 2011). Numerous studies have been conducted to determine the evolution of the climate of central Asia and several explanatory models have been proposed (e.g. Ding et al., 2002; Cheng et al., 2012; Chen et al., 2016). Most of the debate has been concerned with climate change on a sub-orbital scale. In the early research, a cold/humid and warm/dry pattern of climatic variation was proposed based on lake sediment records and climate simulations. These results indicated a humid Last Glacial Maximum (LGM) and a dry early Holocene, and southward/northward movements of the Westerlies movement were thought to be the major cause of climatic oscillations from humid to dry states (Yu et al., 2000). Jin et al. (2012) suggested that both the intensity of the Westerlies circulation and upstream (such as: Mediterranean Sea, Black Sea, Caspian Sea) evaporation dominated the humidity patterns in central Asia, while evidence from loess and lacustrine sediments from Xinjiang revealed a dry LGM (Chen et al. 2008 and 2016; Wang and Feng, 2013). In contrast, however, oxygen isotope

records from speleothems indicate a humid early and mid-Holocene and a dry late Holocene (Cheng et al., 2012; Cai et al., 2017). Although the debate continues regarding the timing and origin of the aridity/humidity variations, it has been widely accepted that the Westerlies play an important role in driving climate change in central Asia.

Eolian dust is regarded as one of the most important tracers of atmospheric circulation (Sun, 2002; Maher, 2016) and analysis of the grain-size distribution of eolian sediments enables the reconstruction of palaeowind systems. In central Asia, the content and sediment rate of coarse grained material had been regarded as the indexes of Westerlies intensity (Ye et al., 2000; Vandenberghe et al., 2006; Li et al., 2016). Subsequently, it had been concluded that the Westerlies strengthened during stadials and weakened during interstadials. And the Westerlies varied as the anti-phase pattern with humidity. However, these conclusions are different with that of simulation research (Jin et al., 2012).

The discrepancies between these conclusions may result from limitations in our understanding of the link between atmospheric circulation and eolian deposits. The presence of several peaks in grain-size frequency distributions has led to the conclusion that loess consists of multiple eolian sources. For example, the grain-size frequency distribution curves of the loess of the Chinese Loess Plateau (CLP) are typically trimodal, which has led to the conclusion that the dust is

* Corresponding author.

E-mail address: jiaj@lzu.edu.cn (J. Jia).

derived from surface circulation and high-level circulation, and in situ production (Sun et al. 2004 and 2011). However, there is a lack of comparable research in central Asia. The coarse grained materials are more likely derived from surface circulation rather than Westerlies, which are controlled by surface pressure centers in winter period, such as Siberian High and Ural blocking (Machalett et al., 2008; Youn et al., 2014).

In this study, we measured the grain-size distribution of central Asian loess deposits and identified a Westerlies component. Combining with a robust chronological framework, the Westerlies variations in central Asia have been reconstructed during the past 16 kyr. And the relationship between Westerlies and the area humidity also has been discussed.

2. Geological setting and study section

Central Asia is far from oceanic moisture sources and thus has an arid climate. The Westerlies are the dominant atmospheric circulation system in the northern part of central Asia in spring and summer. In the autumn, the Siberian-Mongolian High gradually develops and has a significant effect on the atmospheric circulation, resulting in the southern Westerlies replacing the Subtropical High and becoming the dominant atmospheric circulation in the southern part of central Asia (Karger et al., 2016). In addition, the frequent passage of cold fronts is also an important component of atmospheric circulation (Ye et al., 2003).

Due to the prevalent westerly or northwesterly winds, the eolian dust is mainly deposited on the western and northern slopes of the mountains. The Tien Shan and Kunlun Mountains, and the Tajik Depression, are the three most important areas of loess accumulation in central Asia (e.g. Ding et al., 2002; Fang et al., 2002; Chen et al., 2016). Within these areas, thick loess deposits dating to the last deglacial and the Holocene have only been discovered in the North Tien Shan Mountains and in the Ili river valley in Xinjiang, China (Chen et al., 2016).

The Lujiaowan (LJW10) section (43°58′29″N, 85°20′10″E; 1462 m a.s.l.) (Li et al., 2015; Chen et al., 2016) is located in the northern Tien Shan Mountains (Fig. 1). The loess has accumulated on a layer of fluvial gravel layer. We investigated the upper 3 m of the deposit, which consisted of a 1.7-m-thick Holocene paleosol and 1.3 m of underlying loess. The Holocene paleosol can be divided into seven sub-layers, including three dark Holocene paleosols, the uppermost 20 cm of dark-colored modern soil, and three light-colored layers. A detailed description of the profile is given in Chen et al. (2016).

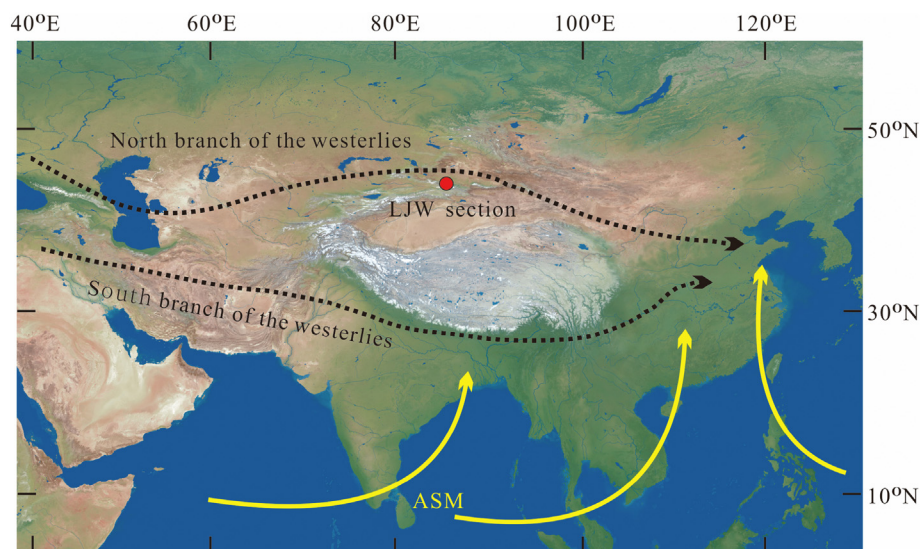


Fig. 1. RS image of central Asia. The red circle indicates the location of the LJW section. Also shown are the dominant atmospheric circulation systems (dashed line) of the Westerlies and Asian summer monsoon (ASM). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Sampling and methods

One hundred and fifty unoriented powder samples were collected at a 2-cm interval. The sediment grain size was measured using the methods of Lu and An (1998). The samples were pretreated by heating in H₂O₂ and HCl, to remove organic matter and carbonates respectively. (NaPO₃)₆ was added and the samples were ultrasonicated to aid dispersion. The grain-size distributions show up with 89 size classes in the range between 0.01 and 2000 μm and were measured using a Mastersizer 2000 laser diffraction particle size analyzer (run length: 20s, with background measurement 10s and background measurement 10s; optical model: Mie Fourier inversion; laser: red and blue), in the Key Laboratory of West China's Environmental Systems, Lanzhou University, China. Subsequently, the grain-size distribution (GSD) data were analyzed using hierarchical alternating least squares non-negative matrix factorization (HALS-NMF) to define individual grain size components (Paterson and Heslop, 2015).

To construct a reliable chronological framework, 14 samples were collected from the LJW10 section at a ~20 cm interval for optically stimulated luminescence dating. Detailed information on the dating of the section is given in Li et al. (2015). The final chronology of the LJW10 section was established using Bacon age depth model (Blaauw and Christen, 2013) based on five coarse-grained quartz ages, eight coarse-grained K-feldspar ages and fourteen medium-grained K-feldspar ages (Li et al., 2015).

4. Results and statistical analysis

4.1. Grain-size measurements

Silt is the major component in the LJW section, with the content ranging from 79.7 to 89.2% ($\bar{x}$ = 83.8%, σ = 2.1%). The clay and sand contents are similar, ranging respectively from 6.7 to 12.2% ($\bar{x}$ = 9.0%, σ = 1.1%) and 3.0 to 11.7% ($\bar{x}$ = 7.2%, σ = 2.0%) (Fig. 2B–D). The mean grain-size ranges from 19.2 to 26.2 μm ($\bar{x}$ = 22.1 μm, σ = 1.5 μm) in the paleosol units, and from 22.3 to 30.8 μm ($\bar{x}$ = 26.2 μm, σ = 1.9 μm) in the loess units. The mean grain-size is close to that of the Xifeng (XF) section, in the central Chinese Loess Plateau (Sun et al., 2010). The standard deviation (σ), skewness (SK), and kurtosis (K) were calculated to further characterize the grain-size distribution of LJW section, using the formulae given in Blott and Pye (2001), with the statistics expressed geometric method of moments. The mean values of σ , SK, K range from 3.0 to 3.7 μm ($\bar{x}$ = 3.4 μm), −1.1 to −0.5 ($\bar{x}$ = −0.7), and 2.5 to 3.8 ($\bar{x}$ = 2.9), respectively, which

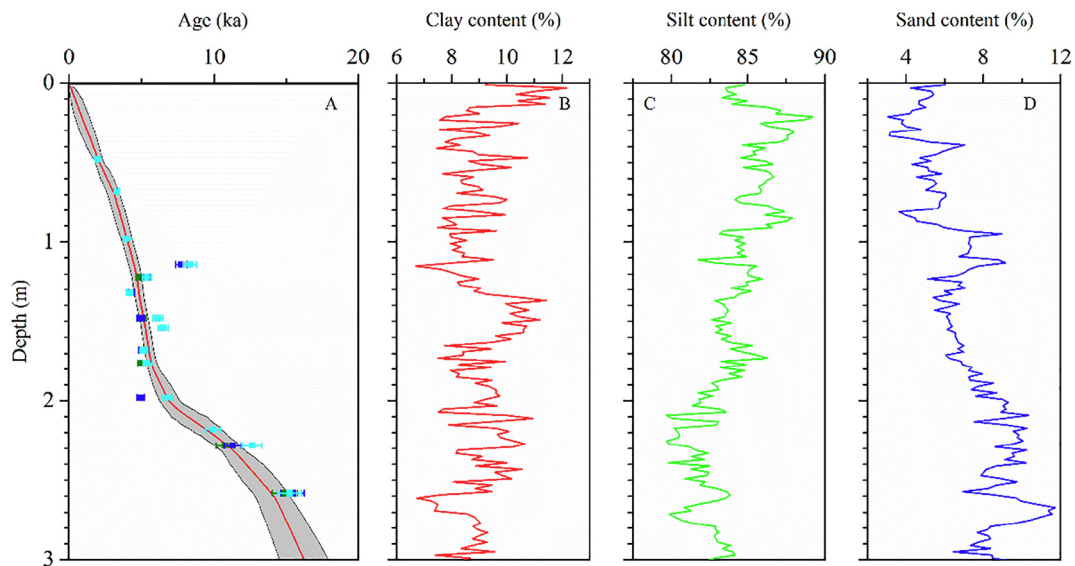


Fig. 2. (A) Chronology and grain-size parameters for the LJW section. Coarse quartz OSL ages (green dots), coarse K-feldspar pIRIR ages (blue dots), and K-feldspar pIRIR ages (cyan dots). (B–D) Variations in contents of different components in the depth of the LJW section (clay: $< 2 \mu\text{m}$, silt: $2\text{--}63 \mu\text{m}$, and sand: $> 63 \mu\text{m}$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicates that LJW loess is poorly sorted, the grain-size distribution is significantly fine-skewed and is mesokurtic.

4.2. End-member analysis

In accordance with being poorly sorted, the grain-size distributions of the LJW are polymodal (Fig. 3A), and at least three modes can be easily distinguished in the gradient curves calculated from the grain-size distribution data (Fig. 3B). To evaluate the number of end-members (EMs) in the grain-size distribution of the LJW loess, we used HALS-NMF and compared the performance of the algorithms by fitting 1–10 EMs to each of the data sets. The coefficient of determination (R^2) and angular deviation, which are used to estimate the accuracy of fitting result (Paterson and Heslop, 2015), exhibits a peak or plateaus correspond to three EMs, which suggests that the LJW loess comprises three grains-size modes (Fig. 3C–E). More evidence for the reliability of the results is provided by a comparison of the grain-size distributions of the original data and the reconstructed curves, which reveals a high degree of similarity (Fig. 3F–H).

The grain-size distributions of the three EMs are shown in Fig. 3E; they are labelled as EM1, EM2, and EM3, and have modal sizes of $1.6 \mu\text{m}$, $11.0 \mu\text{m}$, and $39.8 \mu\text{m}$, respectively. In accordance with a previous interpretation of the origin of the grain size components of loess from the CLP loess (Sun et al., 2011), we infer that EM1 was produced by pedogenesis, and that EM2 and EM3 were transported by the high-altitude Westerlies and near-surface winds, respectively (Sun et al., 2004). It should be noted that the modal size of EM2 is clearly larger than that of the fine-grained component of CLP loess ($3\text{--}6 \mu\text{m}$), and of dust in the sediments of the North Pacific Ocean ($\sim 2 \mu\text{m}$) (Sun et al., 2004), although all three are transported by the Westerlies. The differences in modal size may be the result of the differences between the distances from the dust source area to the site of deposition, with distance decreasing and sedimentary grain-size increasing in the following order: The North Pacific Ocean is thousands of kilometers from the source area and the deposited dust has the finest grain-size, the CLP is hundreds of kilometers from the source area and accumulates relatively coarser dust, and the LJW section is located close to the source area and contains the coarsest dust.

As shown in Fig. 4, the content of EM2 and EM3 vary inversely. EM2 exhibits a generally decreasing trend, from ~ 70 to $\sim 30\%$, while EM3 increases from ~ 20 to $\sim 60\%$. In contrast, EM1 is relatively uniform,

ranging from ~ 12 to $\sim 20\%$. Two abrupt changes in the curves occur at the depths of $2.77\text{--}2.57 \text{ m}$ ($15.1\text{--}13.8 \text{ ka}$) and $2.41\text{--}2.27 \text{ m}$ ($12.3\text{--}10.8 \text{ ka}$).

4.3. Mass accumulation rates (MAR)

The mass accumulation rate (MAR) was calculated using the equation $\text{MAR} = \text{DAR} \times f \times \text{BD}$ (Kohfeld and Harrison, 2003), where DAR is the sediment accumulation rate (cm/year), f is a coefficient (for loess, $f = 1$), and BD is the bulk density (g/cm^3) of sediment. DAR is calculated as:

$$\text{DAR} = \frac{D_{\text{lower}} - D_{\text{upper}}}{A_{\text{lower}} - A_{\text{upper}}} \quad (1)$$

D_{lower} and D_{upper} are the lower and upper depths of the layer, respectively; A_{lower} and A_{upper} are the ages of the bottom and top of the layer, respectively; and BD is the bulk density of the layer. The chronology and grain size analysis results for the LJW section were combined to calculate the DAR of EM2, which varies from ~ 1.9 to $\sim 35.6 \text{ cm/kyr}$ ($\bar{x} = 10.9 \text{ cm/kyr}$) (Fig. 5B). Six samples were selected from the LJW section, from depths of $48\text{--}50$, $120\text{--}122$, $148\text{--}150$, $198\text{--}200$, $228\text{--}230$, and $258\text{--}260 \text{ cm}$, for bulk density measurements. The average bulk density is about 1.42 g/cm^3 in paleosol complex layers, and 1.62 g/cm^3 in loess layers. Subsequently, we used the BD of the bulk samples to estimate the BD of the EM2 component which in turn was used to calculate the MAR of EM2, which varied from ~ 3.1 to $\sim 50.6 \text{ g/cm}^2\text{-kyr}$ ($\bar{x} = 15.9 \text{ g/cm}^2\text{-kyr}$) (Fig. 5C). The variations in DAR and MAR exhibit three stages: (i) From 16 to 6 ka , when the MAR was lowest, ranging from 3.1 to $13.8 \text{ g/cm}^2\text{-kyr}$ ($\bar{x} = 6.7 \text{ g/cm}^2\text{-kyr}$); (ii) from 6 to 3.1 ka , when the MAR ranged from 11.9 to $50.6 \text{ g/cm}^2\text{-kyr}$ ($\bar{x} = 26.8 \text{ g/cm}^2\text{-kyr}$); and (iii) during $3.1\text{--}0 \text{ ka}$, when the MAR varied from 11.3 to $18.8 \text{ g/cm}^2\text{-kyr}$ ($\bar{x} = 14.7 \text{ g/cm}^2\text{-kyr}$).

5. Discussion

5.1. Variation of the westerlies in Central Asia during the last deglacial and Holocene

The dust from the Westerlies can be deposited in three ways: by rainfall wash-out (Rea and Hovan, 1995), by attachment to larger grains (Pye, 1987), and by deposition as individual particles when the

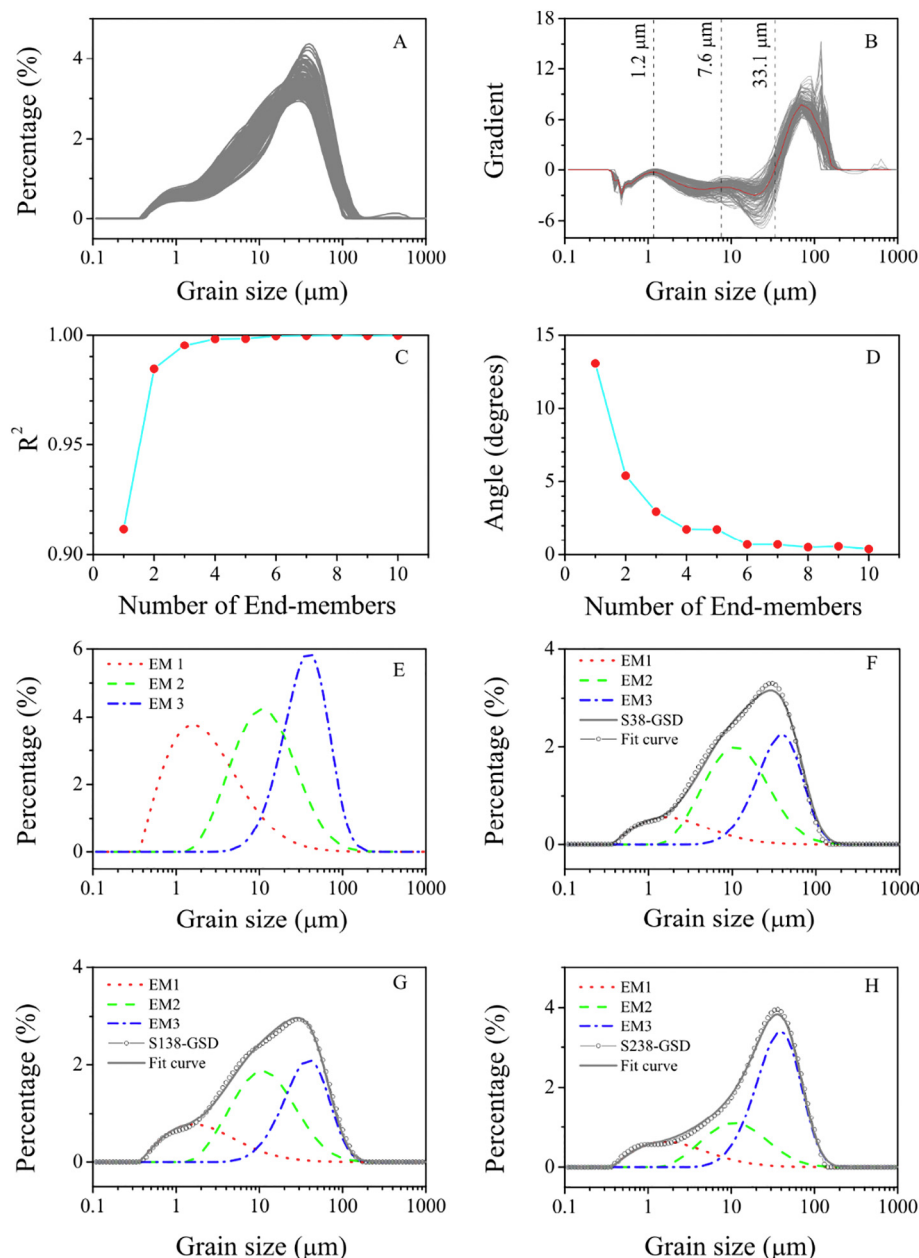


Fig. 3. (A–B) Grain-size distribution curves and their gradient curves for all samples from the LJW section. (C–D) Goodness-of-fit statistics for the unmixing of the data. (E) Grain-size distribution of endmembers. (F–H) Comparison between the original grain-size distribution and fitting results for representative samples.

wind-speed decreases (Sun et al., 2004). In addition, the greater the content of mineral material in the air masses associated with the Westerlies circulation, then the greater the opportunity of forming a dust deposit. Therefore, the high MAR values in the LJW section can be interpreted as corresponding to strong Westerlies circulation and vice versa. The variations of the MAR enable the history of the Westerlies circulation in the Tien Shan Mountains to be reconstructed. The three stages, summarized in Section 4.3, indicate that the weakest intensity occurred during last deglacial and early Holocene (16–6 ka), the greatest intensity in the mid-Holocene (6–3.1 ka, marked in Fig. 5 with blue and green shadows), and moderate intensity in the late Holocene (3.1–0 ka). The result is opposite with the previous studies (e.g. Ye et al., 2000; An et al., 2012; Li et al., 2016).

Although dust emission in arid central Asia was extremely high during the last deglacial (Maher et al., 2010; An et al., 2012; Fig. 5F), our results indicate that in the Tien Shan Mountains area, the Westerlies circulation were relatively weak, especially during Heinrich event 1 and

the Younger Dryas (marked in Fig. 5 with grey shadow). The variation pattern of Westerlies circulation in which is similar to that in Greenland (Mayewski et al., 1997, Fig. 5D). This phenomenon can be explained by two mechanisms: (i) the Westerlies circulation were displaced southward during glacial stages which led to a weakening in the Tien Shan Mountains area (Pullen et al., 2011), which was indicated by a climate simulation study of the change in the location of the Westerlies circulation in the Southern Hemisphere (Wyrwoll et al., 2000), and (ii) the meridional circulation strengthened and the zonal circulation weakened in the Northern Hemisphere during glacial stages. In fact, the increased MAR recorded in many Chinese loess sections during glacial stages was contributed by low-level atmospheric circulation, such as dust storms (Sun et al., 2004).

During the Holocene, the Westerlies, in central Asia, exhibited an out-of-phase relationship with the Asian Summer Monsoon (ASM). The most notable difference is that the Westerlies were weak in the early Holocene, while the ASM was strong (Dykoski et al., 2005; Fig. 5C and

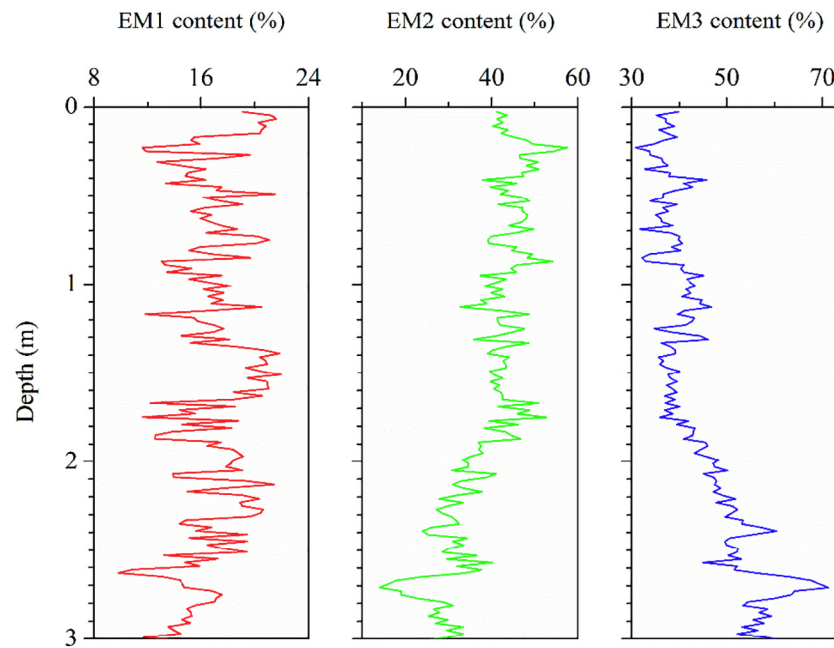


Fig. 4. Depth variations of the content of each endmember component.

E). It has been observed that the location of the Westerlies in central Asia is closely linked with the ASM (e.g. Huang et al., 2015; Karger et al., 2016). The orography of the Tibetan Plateau has a major influence on the atmospheric circulation of Asia, resulting in the deep penetration of the ASM into the interior of the Asian landmass, but forming a vast rain shadow area in central Asia. Modern observations indicate that Westerlies move northward in May, corresponding to an extension of the ASM, and southward in September, corresponding to a retreat of the ASM (Karger et al., 2016). Therefore, an extended ASM

during the early Holocene may have led to a northward movement of the Westerlies and thus a weakening in the Tien Shan Mountains area. In addition, the simulation study indicated an anti-phased pattern of precipitation between central Asia and Monsoonal Asia, in the development of which the circum-global teleconnection ('CGT'; Ding and Wang, 2005) played an important role.

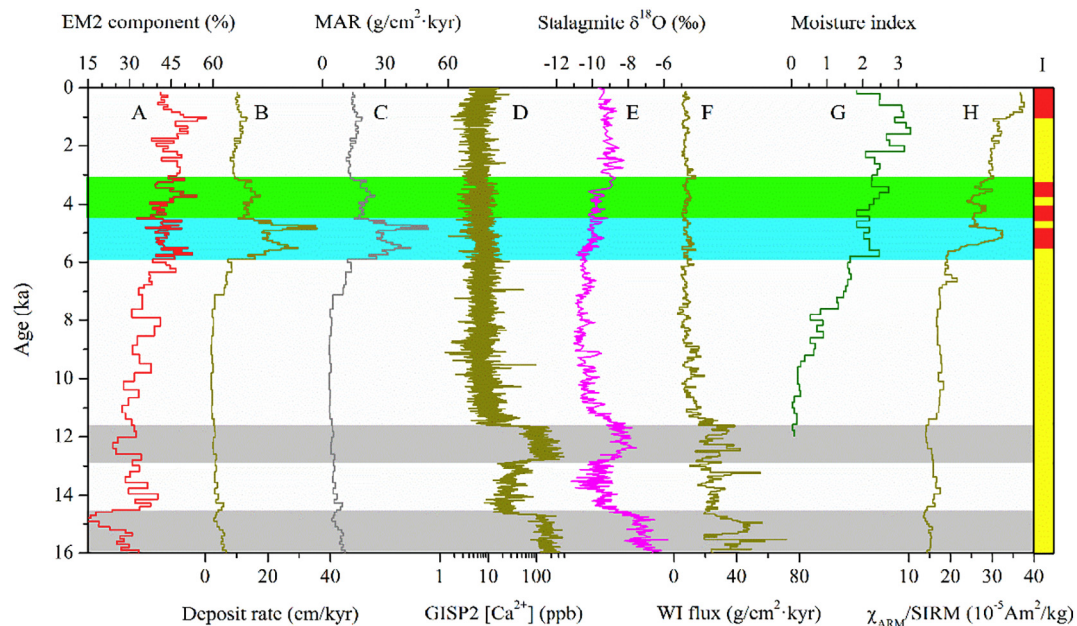


Fig. 5. Variations in the content (A), accumulation rate (B) and mass accumulation rate (MAR) (C) of EM2 in the LJW section. Also shown for comparison are the Ca^{2+} record of the GISP2 ice core (D, Mayewski et al., 1997), an oxygen isotope record from Chinese speleothem deposits (E, Dykoski et al., 2005), an index of Westerlies intensity from the eolian component of sediments of Qinghai lake (F, An et al., 2012), a moisture index from lacustrine sediments from Northern Xinjiang (G, Wang and Feng, 2013), a moisture index from the content of fine-grained pedogenic ferrimagnetic minerals in the LJW section (H, Chen et al., 2016), and the stratigraphy of the LJW section with paleosol and loess layers being marked by red and yellow bars, respectively (I, Chen et al., 2016). The grey shadow marked the periods with weakest Westerlies in central Asia, recorded by LJW section. The blue and green shadows marked the periods with strongest and secondary strongest Westerlies in central Asia, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.2. Relationship between the westerlies and humidity in Central Asia

Modern observations reveal that the Westerlies are the major source of precipitation in central Asia (Karger et al., 2016), while a climate simulation study showed that the intensity of the Westerlies, combined with evaporation upstream, dominated the precipitation in central Asia (Jin et al., 2012). Our results indicate the occurrence of a similar phenomenon, not only during the Holocene but also during the last deglacial. Fig. 5 indicates that a moisture proxy exhibits a similar pattern of variation to the intensity of Westerlies circulation in the Tien Shan Mountains during the past 16 kyr, with high precipitation corresponding to strong Westerlies circulation and vice versa. One example occurred during 6–3.1 ka: three soil units developed during an interval of strong Westerlies circulation (Chen et al., 2016; Fig. 5H and I), and the lakes were at a high level or indicated humid conditions (Wang and Feng, 2013; Fig. 5G). A second example is the correspondence between weak Westerlies circulation during the last deglacial and early Holocene and the development of loessic soil units with a massive structure and the disappearance of lakes (Chen et al., 2016; Wang and Feng, 2013; Fig. 5H and I).

Due to the close link between the Westerlies and precipitation in central Asia, significant local differences in Westerlies circulation will lead to an out-of-phase relationship with precipitation in mid-latitude Asia. Consequently, we suggest that careful attention should be paid to regional differences in future climate change research.

6. Conclusions

We have used detailed grain-size analyses of a well-dated loess section in the Tien Shan Mountains, spanning the last deglacial through the Holocene, to calculate variations in the MAR of dust transported by the Westerlies. The results indicate that the Westerlies circulation was weakest during the last deglacial and early Holocene (16–6 ka), strongest during the mid-Holocene (6–3.1 ka), and moderate during the late Holocene (3.1–0 ka). In addition, based on comparison with a record of moisture variations, we propose that the Westerlies circulation was the dominant control of moisture variations in central Asia, with strong Westerlies circulation resulting in high precipitation and vice versa during the past 16 kyr.

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